

## SPACE STATION WP-2 APPLICATION OF LDEF MLI RESULTS

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## SUMMARY

The Cascaded Variable Conductance Heat Pipe Experiment, which was developed by Michael Grote of McDonnell Douglas Electronic Systems Company, was located in Tray F-9 of the Long Duration Exposure Facility (LDEF), where it received atomic oxygen almost normal to its surface. The majority of the tray was covered by aluminized Kapton® polyimide multilayer insulation (MLI), which showed substantial changes from atomic oxygen erosion. Most of the outermost Kapton layer of the MLI and the polyester scrim cloth under it were lost, and there was evidence of contaminant deposition which discolored the edges of the MLI blanket. Micrometeoroid and orbital debris (MM/OD) hits caused small rips in the MLI layers, and in some cases left cloudy areas where the vapor plume caused by a hit condensed on the next layer. The MLI was bent gradually through 90° at the edges to enclose the experiment, and the Kapton that survived along the curved portion showed the effects of atomic oxygen erosion at oblique angles. In spite of space environment effects over the period of the LDEF mission, the MLI blanket remained functional.

The results of the analysis of LDEF MLI were used in developing the standard MLI blanket for Space Station Work Package-2 (WP-2). This blanket is expected to last 30 years when exposed to the low Earth orbit (LEO) environment constituents of atomic oxygen and MM/OD, which are the most damaging to MLI materials. The WP-2 standard blanket consists of an outer cover made from Beta®-cloth glass fiber fabric which is aluminized on the interior surface, and an inner cover of 0.076-mm (0.003-in) double-side-aluminized perforated Kapton. The inner reflector layers are 0.0076-mm (0.0003-in) double-side aluminized, perforated Kapton separated by layers of Dacron® polyester fabric. The outer cover was selected to be resistant to the LEO environment and durable enough to survive in orbit for 30 years.

This paper describes the analyses of the LDEF MLI results, and how these results contributed to the selection of the WP-2 MLI blanket materials and configuration.

## INTRODUCTION

Multilayer insulation (MLI) blankets, consisting of loose layers of flexible, highly reflective material, provide effective, light-weight thermal insulation for spacecraft systems operating in vacuum. They will be used on the propellant tanks and on many fluid lines of the Space Station *Freedom* (S.S. *Freedom*), where the design of the MLI blankets was based to a large part on post-flight characteristics of MLI on the LDEF satellite, in particular the heat pipe experiment No. A0076. This paper describes the effects on MLI of 6 years of exposure to the LEO environment on LDEF, and the development of an MLI blanket suitable for thirty years exposure on the space station.

In addition to the LEO effects on blanket materials seen on the LDEF, requirements for Work Package 2 MLI blankets include thermal cycling, deep temperature excursions, particle radiation exposure, plasma and sputtering interactions, outgassing, and flammability requirements. The blankets must also survive handling on orbit and on ground during installation. Materials must meet NASA requirements which specify that mass loss must not exceed 1 percent of total mass and volatile condensable materials must be less than 0.1 percent during prolonged vacuum exposure. Materials must also pass a vertical burn test per NASA NHB 8060.1 (ref. 1)

## LDEF EXPERIMENT DESCRIPTION AND RESULTS

The LDEF Cascaded Variable Conductance Heat Pipe Experiment No. A0076 was covered on all sides by MLI, which was critical to the proper functioning of the experiment. The experiment was developed by McDonnell Douglas Electronic Systems Company to demonstrate precise temperature control of systems in space with no power consumption, using variable conductance heat pipes. Variable conductance heat pipes carry more or less heat to a radiator as the temperature of the heat producing equipment increases or decreases (ref. 2). Each heat pipe used ammonia as the working fluid. Nitrogen was the control gas, and was contained in a reservoir separated from the heat pipe by a long capillary tube which prevented the ammonia from transferring to the reservoir. For this experiment the temperature of a black chrome solar absorber was regulated by two cascaded heat pipes which transferred heat to a silver-Teflon® radiator. The experiment was successful, with temperature control within 0.3 °C of the set point being achieved over a period of at least 45 days (the length of data recording), despite widely varying thermal loads on the solar absorber. Testing after retrieval of LDEF showed that the temperature control band width was the same as in preflight tests, although the temperature set-point of the heat pipes had shifted slightly as expected.

The experiment was located in Tray F-9 of LDEF, where it received an atomic oxygen (AO) flux of  $8.32 \times 10^{21}$  atoms/cm<sup>2</sup> almost normal to its surface, and 11,100 equivalent sun hours (ref. 3). The majority of the tray was covered by aluminized Kapton® polyimide MLI blankets, which also covered the inner sides and bottom of the tray. The outermost layer of the MLI was a 0.076-mm (0.003-in) unperforated Kapton light block, aluminized only on the inner side, and all other layers were 0.0076-mm (0.0003-in), double aluminized, perforated Kapton. There was a total of 15 layers of 0.0003-in Kapton under the 0.003-in layer. All were separated by polyester scrim cloth to minimize heat leaks between layers. The MLI blankets were attached to the sides of the experiment tray using Velcro® tape.

### Results of LDEF Space Exposure

The exposed MLI showed substantial changes caused by atomic oxygen erosion and debris particle impact. The appearance of the experiment changed from the bronze color of the outer Kapton layer to the shiny metallic finish of the exposed aluminizing. Most of the exposed outermost Kapton layer of the 0.076-mm (0.003-in) MLI and the polyester scrim cloth under it were lost, and there was evidence of contaminant deposition which discolored the edges of the MLI blanket. Some of the aluminizing on the back of the Kapton remained in place after the Kapton was eroded. This aluminizing shielded sections of the scrim cloth during the remainder of the exposure and accounted for the survival of some areas of the scrim cloth. During recovery and after landing, the extremely thin aluminum drifted away from the experiment. The aluminizing on the underlying double aluminized Kapton layers remained firmly attached and protected the Kapton from the space environment.

Meteoroid and debris hits caused small penetrations and rips in the MLI layers, and in some cases left cloudy areas where the vapor plume caused by a hit condensed on the next layer. An example of this is shown in Figures 1 to 7. A particle struck the 0.076-mm (0.003-in) thick outer layer of the MLI before that layer was completely eroded away by the atomic oxygen, and it produced a debris plume which hit the next 0.0076-mm (0.0003-in) thick Kapton layer, causing rips and perforations. These are shown in Figures 1 to 3. Most of the plume was stopped by the first 0.0076-mm (0.0003-in) layer, and the only place where the plume reached the second 0.0076-mm (0.0003-in) layer was at the vent hole, where the impact of the plume ripped and perforated it. Figure 4 shows the vent hole and the impact area, with the shadow of the scrim cloth. Figures 5 to 7 show higher magnifications of the impact area and of the rips and perforations caused by the debris plume.

Because the MLI was bent gradually through 90° at the edges in order to attach it to the Velcro strips on the side of the tray, the Kapton which survived along the curved portion showed the effects of atomic oxygen erosion at oblique angles, as shown in the scanning electron microscope photograph, Figure 8.

There were no visible changes in the MLI blanket which was underneath the experiment. It was shielded from solar radiation, atomic oxygen, and debris by the exposed MLI layer and by the parts of the experiment.

### Effects of MLI Degradation on Spacecraft Systems

The aluminum flakes from the experiment could have degraded the performance of any optical experiments if they drifted into the field of view. The flakes had a large area for their mass and would have drifted away from a spacecraft in low earth orbit fairly rapidly because of the drag of the residual atmosphere, but there would be a possibility of interference until that time. All of the Kapton lost by erosion is converted to volatile products, adding to the density of released gases around the spacecraft and possibly interfering with some experiments requiring unobstructed viewing in the infrared spectral region. The effects of the debris hits on the thermal insulation effectiveness of the MLI was minimal, since it simply added a few more venting perforations to the MLI. In spite of space environment effects over the period of the LDEF mission, the MLI remained functional, and all except the top layer (the light block) survived.

### Space Station WP-2 Blanket Requirements

LDEF results have shown that careful selection of blanket materials is required to meet the thirty year lifetime requirements of the S.S. *Freedom*. MLI materials exposed to LEO must be resistant to AO, micrometeoroid and orbital debris impacts (MM/OD), temperature cycling, excursions outside the normal operating temperature range, ultraviolet (UV) radiation, vacuum, and low levels of particle radiation (ref. 4). MLI materials must remain durable and flexible in order to resist damage from flexure due to thermal cycling, astronaut handling on EVA, thruster plume impingement, or physical abrasion, and must not create significant contamination in the form of particulates or outgassing products.

### Atomic Oxygen Effects on WP-2 Blankets

LDEF has shown that exposed organic materials commonly used in the design of MLI are susceptible to AO erosion. LDEF also confirmed that AO is primarily a "line-of-sight" phe-

nomenon, and that providing some type of protective cover over susceptible materials will be sufficient to shield them from significant AO exposure. LDEF showed that erosion of organic layers can have a secondary contamination effect as evidenced by the erosion of Kapton from the single sided aluminized Kapton, releasing aluminum particles that could pose a contamination concern for the space station.

LDEF also showed the need to prevent any organic thread, commonly used in the manufacturing of MLI blankets, from exposure to the LEO environment. Organic thread will be eroded in a similar manner to that of the polyester separator scrim between reflector layers of the LDEF MLI blankets. The loss of the thread along the seam will cause the blanket to lose its structural stability and could allow layers of the blanket to drift away.

### Thermal Cycling

The space station will be exposed to 100,000 day-night cycles during its 30-year lifetime. These cyclic solar exposures may cause significant temperature excursions during the cycling of the materials with low thermal mass, which will cause stresses in the materials especially when there is a difference in the thermal coefficient of expansion between materials. This stress may cause fatigue and resulting structural failure and shedding of particulates. Also, in materials such as ceramic fabrics, thermal contraction and expansion of the fabric could cause the fibers to abrade against each other and lead to fiber breakage and particle shedding.

### Plasma Interactions

Plasma interactions with the material must also be considered. Because the S.S. *Freedom* truss structure is at a different potential than the surrounding plasma, sputtering and arcing of the exterior materials is possible. NASA tests using artificially created plasma have shown that chromic acid anodized aluminum coatings exhibit a breakdown voltage of as little as 80 V, depending on coating thickness. A potential difference greater than the breakdown voltage may cause local areas to be removed by sputtering due to arcing between the structure and the plasma (ref. 5). Depending on the final design of the S.S. *Freedom*, there could be a potential difference of as much as 120 V between the S.S. *Freedom* and the surrounding plasma. To prevent the sputtering of materials, coatings susceptible to plasma interactions are restricted from direct exposure to the LEO environment.

## SPACE STATION WP-2 BLANKET DEVELOPMENT

MDA has developed an MLI blanket design which is expected to be compatible for 30 years in the S.S. *Freedom* LEO. This design is based on our understanding of material interactions which we gained from the LDEF experiment and from thermal system requirements. The blanket includes a 0.2-mm (0.008-in) thick polytetrafluoro-ethylene (PTFE) impregnated, single aluminized Beta™ glass cloth with the aluminized side facing inward, 20 layers of a light weight separator scrim alternating with 19 layers of a 0.008-mm (0.0003-in) double aluminized polyimide film, and a 0.076-mm (0.003-in) thick scrim reinforced double aluminized polyimide. The general blanket layout is shown in Figure 9.

## Outer Cover

The purpose of the outer cover is to provide a durable surface which can be safely handled by astronauts on EVA and which will prevent damage to the internal layers of the blanket. The outer cover also shields the internal materials of the blanket from ultraviolet radiation, atomic oxygen, and plasma. The small penetrations through the outer cover from MM/OD, as seen on the LDEF blankets, are expected to affect a small percentage of the blanket surface area, and will not significantly affect the thermal performance or structural integrity of the blanket.

The industry standard for a durable, EVA compatible outer cover on MLI has been PTFE impregnated Beta glass cloth. At MDA, Beta™ cloth has been used on a number of different programs on Delta and Titan III launch vehicles and the Payload Assist Module. A PTFE impregnated Beta glass cloth has also been the standard outer cover material for the Orbiter blankets. Flight experience has shown few problems. Orbiter Beta glass cloth has turned yellow after prolonged exposure to UV radiation (ref. 6). This was primarily attributed to the methylsiloxane sizing used during the weaving of the Beta glass fabric. The methylsiloxane sizing may be removed by a high temperature exposure which burns off the silicone resin leaving only the woven glass fabric. Also, the fabric may be woven with or without Teflon sizing.

Testing at NASA-JSC by Dr. Steve Koontz indicates that Beta glass cloth is acceptable for 30 years use as the MLI outer cover. Mechanical testing on the Beta glass cloth included flexing for over 100,000 cycles after atomic oxygen exposure to simulate thermal stresses and fiber-fiber abrasion caused by 30 years of day-night cycle exposures, tear resistance test, and a dart drop impact resistance test. No particulate generation or significant loss in durability of the cover was seen. Analysis of satellite data has shown that atomic oxygen does not penetrate through the fiber bundles of the Beta glass cloth.

Beta glass cloth, while providing a barrier for atomic oxygen, allows approximately 25 percent through transmittance of solar radiation to the underlying layer. Previous MLI designs incorporated the use of a light block layer, and the feasibility of using a traditional light block in the WP-2 MLI blankets was investigated. The traditional light block is a single aluminized Kapton or Mylar layer that serves as a second surface mirror, with a much higher infrared emittance facing away from the blanket than toward it. It prevents an increase in temperature in the reflector layers by preventing solar radiation from striking the reflector layers and by radiating infrared radiation away from the blanket. This improves the thermal efficiency of the blanket.

The primary concern with using an organic material is erosion from atomic oxygen. While the light block is situated beneath the Beta glass outer cover, small penetrations from micrometeorites and debris will occur, allowing atomic oxygen into the lower layers. Although these penetrations represent a small fraction of the total surface area of the blanket, erosion would still occur to the underlying organic layer. As the orientation of the blanket changes with respect to the AO ram direction during the various flight modes, the area exposed to the atomic oxygen flux increases and will cause considerably more degradation to the underlying layers.

The effort to develop an outer cover that was AO resistant, opaque to solar radiation, flexible, and durable, and that was compatible with the LEO environment started with a commercially available, lightweight aluminized glass fabric. This lightweight glass fabric is constructed with large open weaves which are impregnated with Teflon on which a continuous aluminum film can be deposited. The cloth has been used on the Payload Assist Module (PAM) manufactured at MDA, which places satellites into geosynchronous transfer orbits. Testing for LEO compatibility was performed by

NASA-JSC, and showed that this cloth was unacceptable for use because prolonged AO exposure would result in the loss of the impregnated Teflon and the aluminized backing.

The use of an aluminized layer on Beta cloth was explored, since AO asher tests had shown that the tight weave of the Beta cloth might block AO penetration. In addition, McDonnell Douglas Electronic Systems Company (MDESC-St. Louis) has used an aluminized Beta glass on several space applications. These materials utilize a plasma etch pretreatment of the PTFE impregnated Beta cloth to increase the adhesion of the vapor deposited aluminum to the Teflon impregnate. A pretreatment in which a silica based material was incorporated into the Teflon impregnate to provide a more stable and adhesion promoting surface for the aluminum was also investigated. Beta cloth with silica, aluminized with 1,000 Å of aluminum, was evaluated by NASA-JSC for compatibility with the LEO environment. The NASA-JSC evaluation reached the conclusion that the material would withstand thirty years of LEO, and it was chosen for the space station MLI blankets (ref. 6).

### Separator Layers

The material selection for the separator layers depends on the expected service temperature of the blanket and on minimizing blanket weight. The current baselined material is a lightweight polyester netting (Dacron®) which has been used on Delta for low to moderate temperature applications. The netting is known to shrink and melt at temperatures above 177 °C (350 °F). MDA tests have shown that after 48 hours at 350 °F, blankets made with Dacron separators shrink up to 4 percent, and the separator layers have shown some adhesion to the reflector layers. The shrinkage of the separators may result from stress relief of the netting, which is created from denser, heavier netting which is heat stretched to form a lower areal density netting. To insure that the Dacron shrinkage does not affect the blanket performance or dimensions, the maximum use temperature for the separator layers is 121 °C (250 °F). For higher temperature applications, a lightweight weave of Nomex® (polyamide) thread has been selected for use as the separator layers.

### Reflector layers

Two of the most common materials used in the aerospace industry for reflector layers in MLI are aluminized Mylar® and aluminized Kapton®. Past spacecraft programs at MDA have considered the upper temperature limit of aluminized Mylar to be 200 °F, depending on how sensitive the design is to blanket shrinkage. Present calculations of S.S. *Freedom* Propulsion Module temperatures have indicated that insulation which is used to control the temperature of the hydrazine fuel tanks on the module could be exposed to temperatures in excess of 149 °C (300 °F) during reboost thruster operation.

A comparison of Mylar and Kapton properties from the MAPTIS data base (ref. 7) is shown in Table 1.

Table 1. Mylar and Kapton property comparison.

PROPERTY	MYLAR	KAPTON
Transition Temperature	80 °C (176 °F)	360 °C (680 °F)
MAPTIS Flammability Rating Notes: "A" - passes NHB8060.1 Test 1 "X" - fails NHB8060.1 Test 1	"X" at 0.091 mm (0.006 in) thick, 25.9% and at 30.0% oxygen	"A" at 0.051 mm (0.002 in) thick, 25.9% oxygen, "A" at 0.076 (0.003 in) thick, 30.0% oxygen
Residual Shrinkage at 300 °F	1.5 %	0.2 %

MDA plans to use Kapton in the MLI blankets because Mylar does not meet temperature requirements in applications where the blankets may be exposed to the high temperatures previously noted and because the use of Kapton will prevent potential on-orbit fit problems due to material shrinkage. From a thermal standpoint, excessive blanket shrinkage is undesirable because of movement in the blanket assembly in joint and penetration areas, decreasing overlaps and area coverage, and stressing blanket attachments. The use of Kapton also allows vacuum baking of the MLI materials and assemblies at 121 °C (250 °F) to meet outgassing requirements.

Neither Kapton nor Mylar meet flame propagation requirements for the Orbiter Cargo Bay at the thicknesses used for reflector layers, 0.0076 mm (0.0003 in). Both films must be encapsulated and tested in configuration. Generally, inner and outer blanket covers (usually 0.0051- to 0.0076-mm thick Kapton or Beta cloth) meet flammability requirements, and the blanket, when tested as an assembly, meets the flammability requirement.

The number of reflector layers was selected to be 19 layers for WP-2. This number was based on previous MDA experience that blanket thermal performance starts to level out around 10 to 12 layers and reaches a maximum performance around 15 layers. The additional four layers allows some damage due to small MM/OD impacts without affecting blanket performance.

### Inner Cover

The inner cover of the blanket will face the hardware, and like the outer cover, it must be durable to prevent damage to the inner layers caused by handling during ground installation and on-orbit. A number of different materials such as glass cloths and aluminized Mylar or Kapton layers have been used by MDA on previous programs. To meet the thermal optical and durability requirements, 0.076-mm (0.003-in) double aluminized Kapton was selected. The aluminized Kapton will be reinforced with a Nomex scrim to provide added strength and tear resistance to the film. The maximum infrared (IR) hemispherical emittance of the aluminized inner cover is expected to be 0.04, so that the majority of the radiation will be radiated to space rather than to the interior of the blanket.

### Thread

LDEF results have shown that organic thread material such as Nomex will be eroded when exposed to atomic oxygen. To prevent seams and sewn joints from degrading and coming apart, the thread used must to sew blankets must be either compatible with atomic oxygen or protected from it. The thread must be strong enough to endure the sewing process, tend not to easily shred and generate particulates, and be compatible with the low earth orbit environment if exposed. Thread must

also be manageable for easy manufacturing. For applications where thread will be protected from atomic oxygen, Nomex will be used.

For those applications where thread may be exposed to atomic oxygen there are several possibilities. While a number of different materials such as quartz or aluminum borosilicate (Nextel™) are resistant to atomic oxygen and UV radiation, MDA has found that they are difficult to use to sew seams. The quartz and Nextel threads tend to wear away the needles of the sewing machines, causing the thread to snag and break. This thread breakage is unacceptable on a manufacturing scale in which many blankets must be fabricated. MDA plans to use a polyamide coated Beta glass thread to sew high temperature MLI blankets that reach temperatures above the maximum use temperature of the Nomex threads. The thread is less flexible than the Nomex, but does not tend to shred and break as much as the quartz or Nextel threads. This thread is atomic oxygen resistant, although the coating will erode, and is expected to provide an adequate seam over the 30-year exposure to the LEO environment.

### Fasteners

Hook and loop fasteners have been identified as an EVA compatible method to fasten MLI blankets to other surfaces. MIL-F-21840 type 2, class 1 hook and loop fasteners are the primary method for attaching blankets to underlying surfaces or to each other. The material meets outgassing requirements; however, it must be used in limited amounts to meet the flammability requirements. The current limitation on use of the material is two square inches of fastener separated by a minimum of two linear inches from other fastener material.

The MIL-F-21840 fastener is constructed from a 0.127-mm (0.005-in) thick nylon loop. Since nylon is eroded by atomic oxygen, precautions must be taken to insure that the fastener is not exposed to atomic oxygen. It was arbitrarily decided that the fastener could be exposed to atomic oxygen for a total of two weeks, while the blankets were opened for servicing, tests, or component replacement, before its peel strength and use life was shortened extensively. This period represents the amount of time required for atomic oxygen in direct ram orientation to erode one half of the thickness of the hook or loop section.

Fasteners may be attached to the blanket by either stitching or adhesively bonded, and may either be adhesively bonded or riveted to the underlying structure. Continuous temperature cycling between the lower and upper limits of the touch temperatures  $-118^{\circ}\text{C}$  ( $-180^{\circ}\text{F}$ ) and  $+113^{\circ}\text{C}$  ( $235^{\circ}\text{F}$ ) is not expected to degrade the mechanical performance of the MIL-F-21380 hook and loop fasteners.

Metallic hook and loop fasteners are commercially available and are resistant to atomic oxygen. They were not seriously considered because they begin to lose their mechanical properties after a limited number of cycle lives, and they would be a safety concern for extravehicular activity (EVA) because they may rip or abrade the outer layer of the astronaut's suit.



## CONCLUSION

The results of MLI exposure to the LEO environment on LDEF, combined with the experience on other space programs at MDA and other companies, have been used to develop a light weight MLI blanket which gives excellent thermal performance and provides confidence that the blanket will last for 30 years in LEO on the space station.

## REFERENCES

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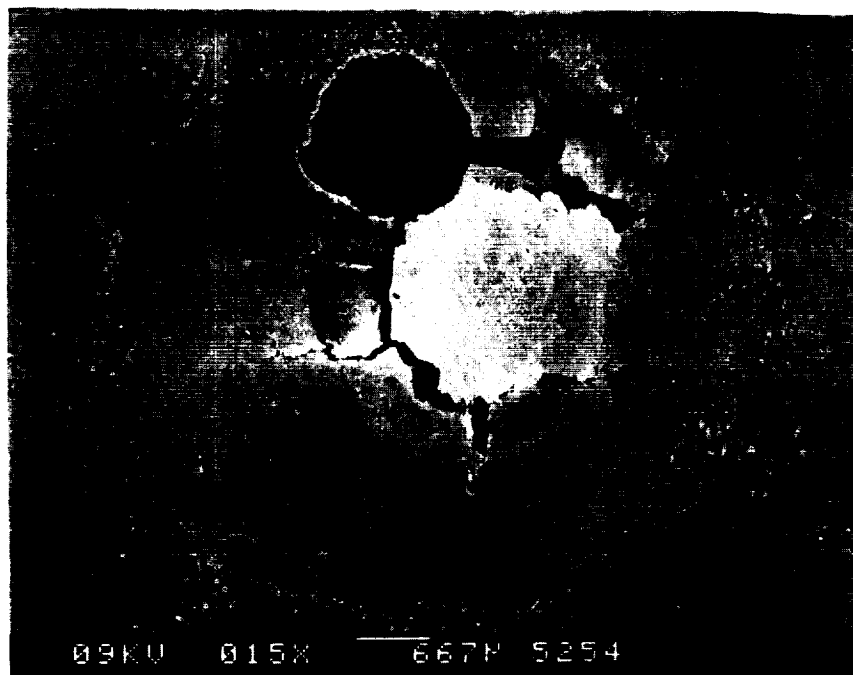


Figure 1. Debris impact area of second Kapton layer, SEM,  $\times 15$ .

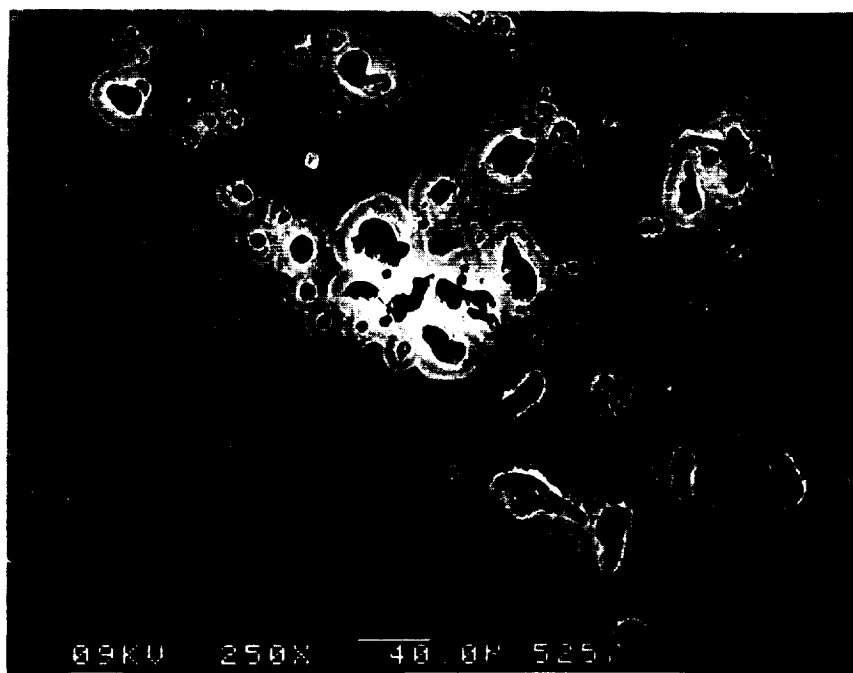


Figure 2. Debris impact area of second Kapton layer, showing perforations, SEM,  $\times 250$ .

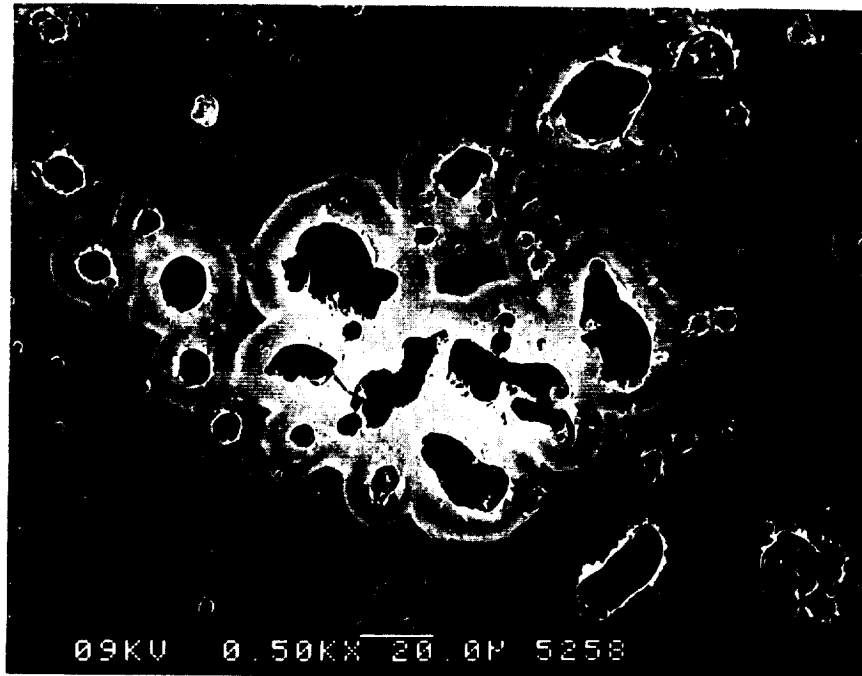


Figure 3. Debris impact area of second Kapton layer, showing undercutting, SEM,  $\times 500$ .



Figure 4. Third Kapton layer, showing impact of plume through vent hole of second layer, optical photograph,  $\times 10$ .



Figure 5. Same area of third Kapton layer, SEM,  $\times 100$ .

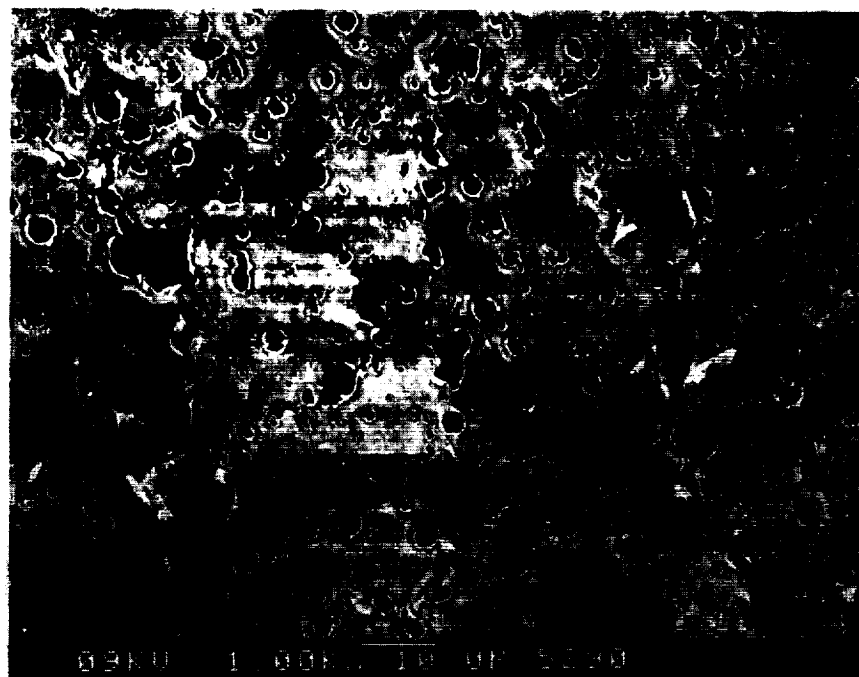


Figure 6. Same area of third Kapton layer, showing rips and perforations, SEM,  $\times 1,000$ .

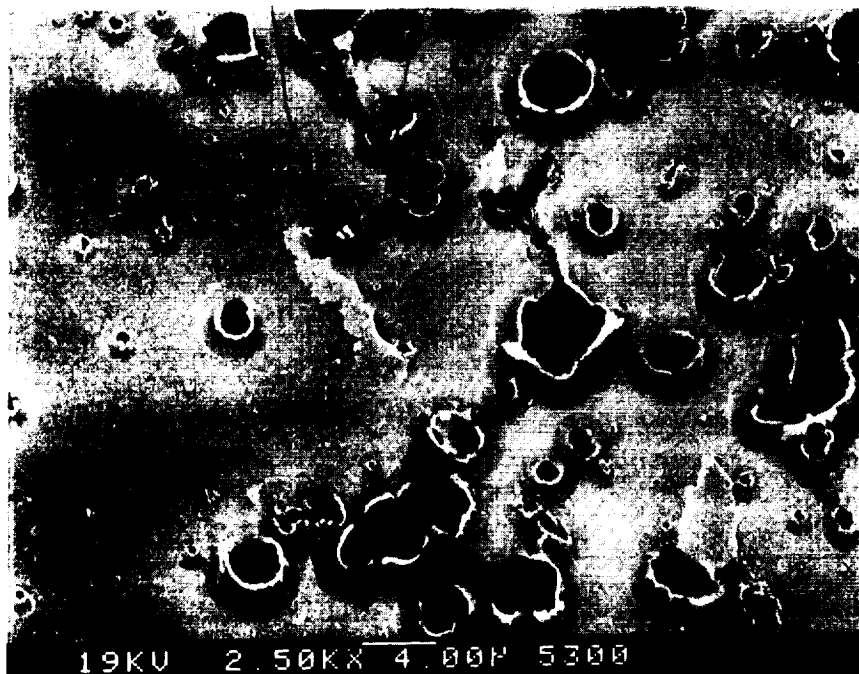


Figure 7. Third Kapton layer, showing a small particle with high titanium, possibly paint, SEM,  $\times 2,500$ .

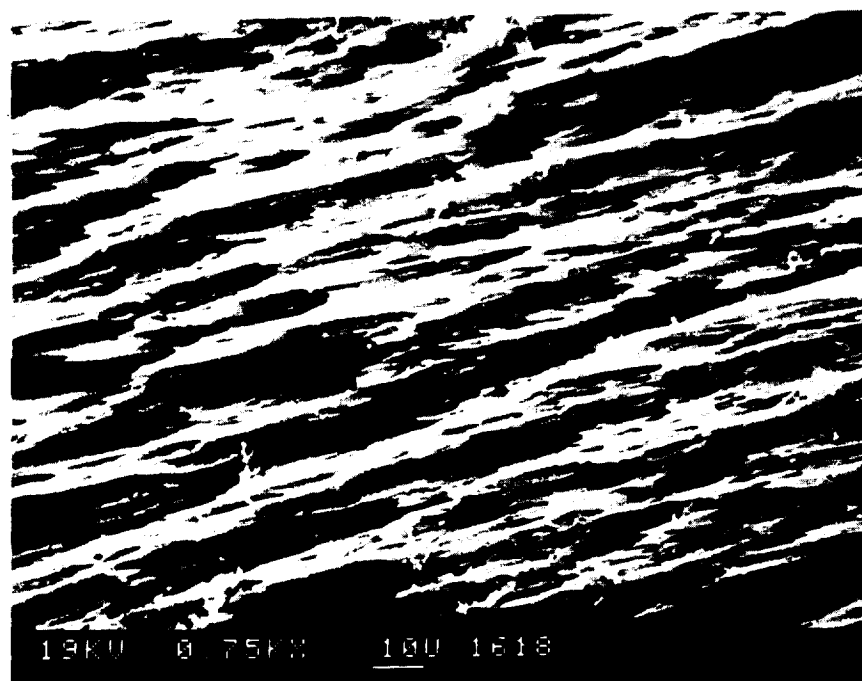


Figure 8. SEM photograph of the aluminized Kapton lightblock exposed to AO at a very oblique angle, SEM,  $\times 750$ .

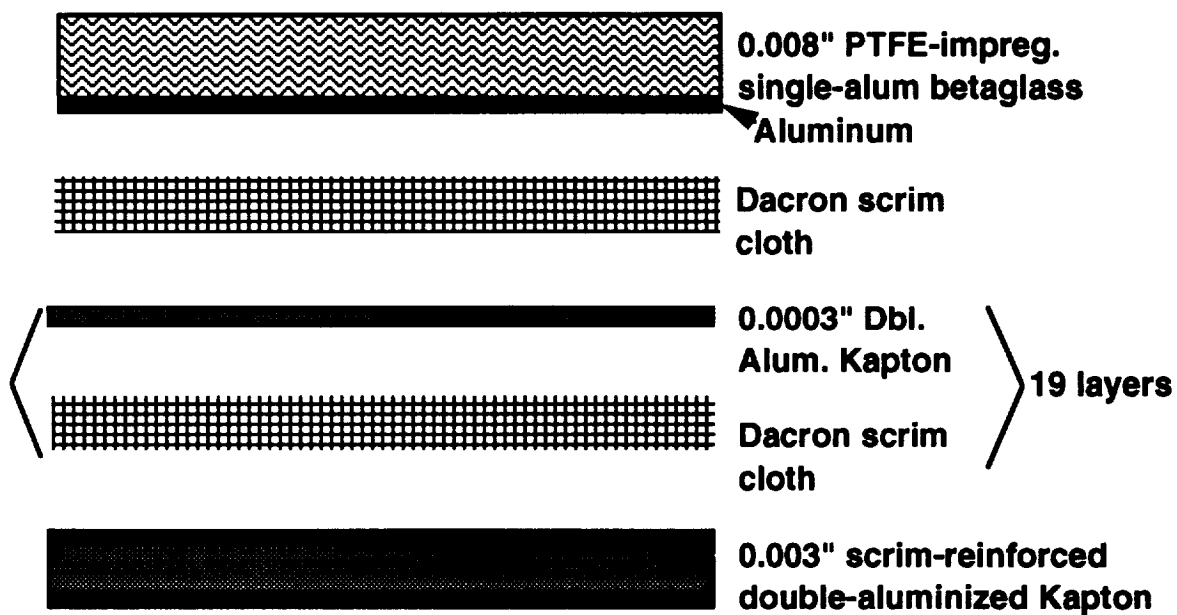


Figure 9. Layers of the space station MLI blanket and their arrangement.